

Hydrogeochemistry for mineral exploration in Western Australia (II): Case Studies

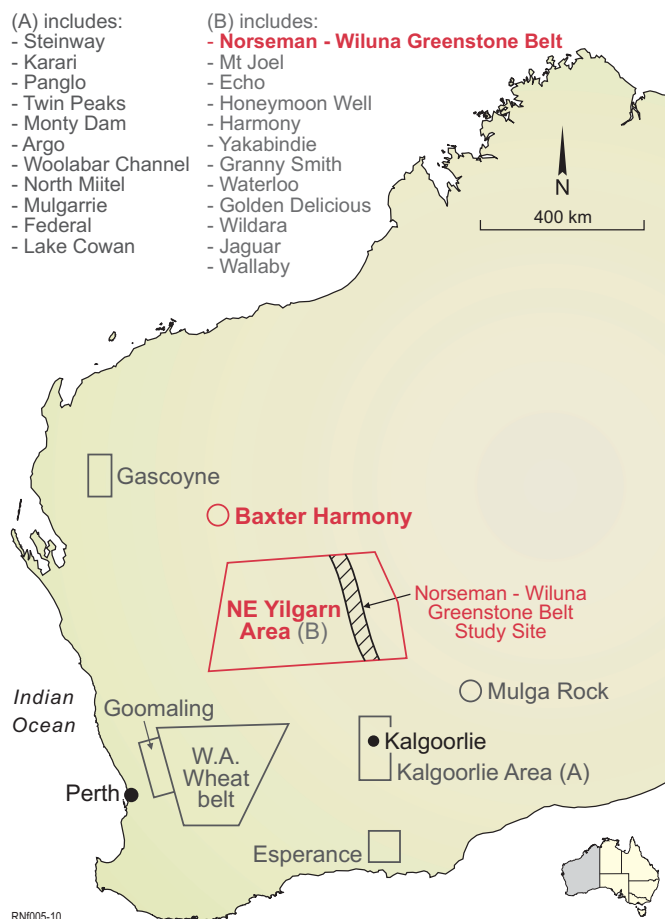


Figure 1. Map of Western Australia showing general regions where hydrogeochemical exploration methods have been applied. The bold text shows the location of the case study site.

INTRODUCTION

Mineral deposits are becoming more difficult to find and greater emphasis is being placed on exploring through deep (>30 m) transported cover and into basin terrains. Groundwater interacts with mineralized rocks and can display a geochemical signature with a much greater footprint than other sampling media, as groundwater is mobile (Cameron 1978; Giblin & Dickson 1992; Leybourne & Cameron 2006; Taufen 1997). The larger size of groundwater geochemical anomalies can reduce the required drilling density needed to explore in a region, an important consideration for cost-effective exploration in covered

terrains.

The application of hydrogeochemistry for mineral exploration is valuable in Western Australia and other parts of the world, and is particularly useful for early-stage exploration and development of regional targets (Gray *et al.* 2009; de Caritat *et al.* 2005; Taufen, 1997). Research by Carey *et al.* (2003), Gray (2001), Gray & Noble (2006) and Gray *et al.* (2009) has advanced the use of exploration hydrogeochemistry in Western Australia, while Kirste *et al.* (2003), Pirlo & Giblin (2004) and de Caritat *et al.* (2005) have successfully applied groundwater exploration methods in other parts of Australia. Outside of Australia, extensive groundwater research for mineral exploration has been conducted in North America (Boyle *et al.* 1993; Gillis *et al.* 2004; Leybourne *et al.* 2000; Phipps *et al.* 2004), South America (Cameron *et al.* 2002; Cameron & Leybourne 2005; Leybourne & Cameron 2006) and elsewhere (de Caritat *et al.* 2009; Pauwels *et al.* 2002). This paper presents results from a number of sites used for hydrogeochemical investigations in Western Australia (Fig. 1). The groundwater was collected and analysed by the procedures of Noble & Gray (2010).

CASE STUDIES

Harmony Au Deposit – A local scale investigation of Au

The Harmony Au deposit is located within a depositional plain approximately 9 km west of Peak Hill and 90 km north of Meekatharra in Western Australia (Fig. 1). The region is arid, with low, irregular rainfall averaging 240 mm per annum (Bureau of Meteorology, 2008). The sparse vegetation consists largely of mulga (*Acacia aneura*), and drought-resistant shrubs and grasses. The deposit was discovered in 1991 by RAB drilling to saprolite and fresh rock, although, in retrospect, sampling of groundwater, buried laterite and the basement-cover interface would have also been successful (Robertson 2001; Robertson & Gray 2003).

The site is located in the Palaeoproterozoic Bryah Basin. The mineralization is on the contact between the Ravelstone and Narracoota Formations. The Ravelstone Formation is a thick turbidite sequence of fine-grained, mafic, feldspathic and lithic wackes. Folded ultramafic and mafic volcanics comprise the Narracoota Formation. The sequences are metamorphosed to lower to middle greenschist facies (Pirajno & Occhipinti 1995; Pirajno *et al.* 1995). Primary mineralization is associated with hematitic quartz veins and carbonate-filled breccia, with Au and Ag occurring as inclusions in pyrite with associated pyrrhotite, pentlandite, chalcopyrite and scheelite. Trace element signatures in the mineralized rocks include As, Te, Zn and Pb, with Au and W the most useful pathfinders (Harper *et al.* 1998).

The deposit has been weathered to ferruginous saprolite and covered by colluvium-alluvium. Colluvium-alluvium in the area is 7-12 m thick, but directly over the deposit (a palaeo-high) it is 1-3 m thick. The upper few metres of the colluvium-alluvium are silicified to a red-brown hardpan. Below this, the material is similar, but finer grained and uncemented. Adjacent to the deposit, but beneath the colluvium-alluvium, the deposit is flanked by a lateritic

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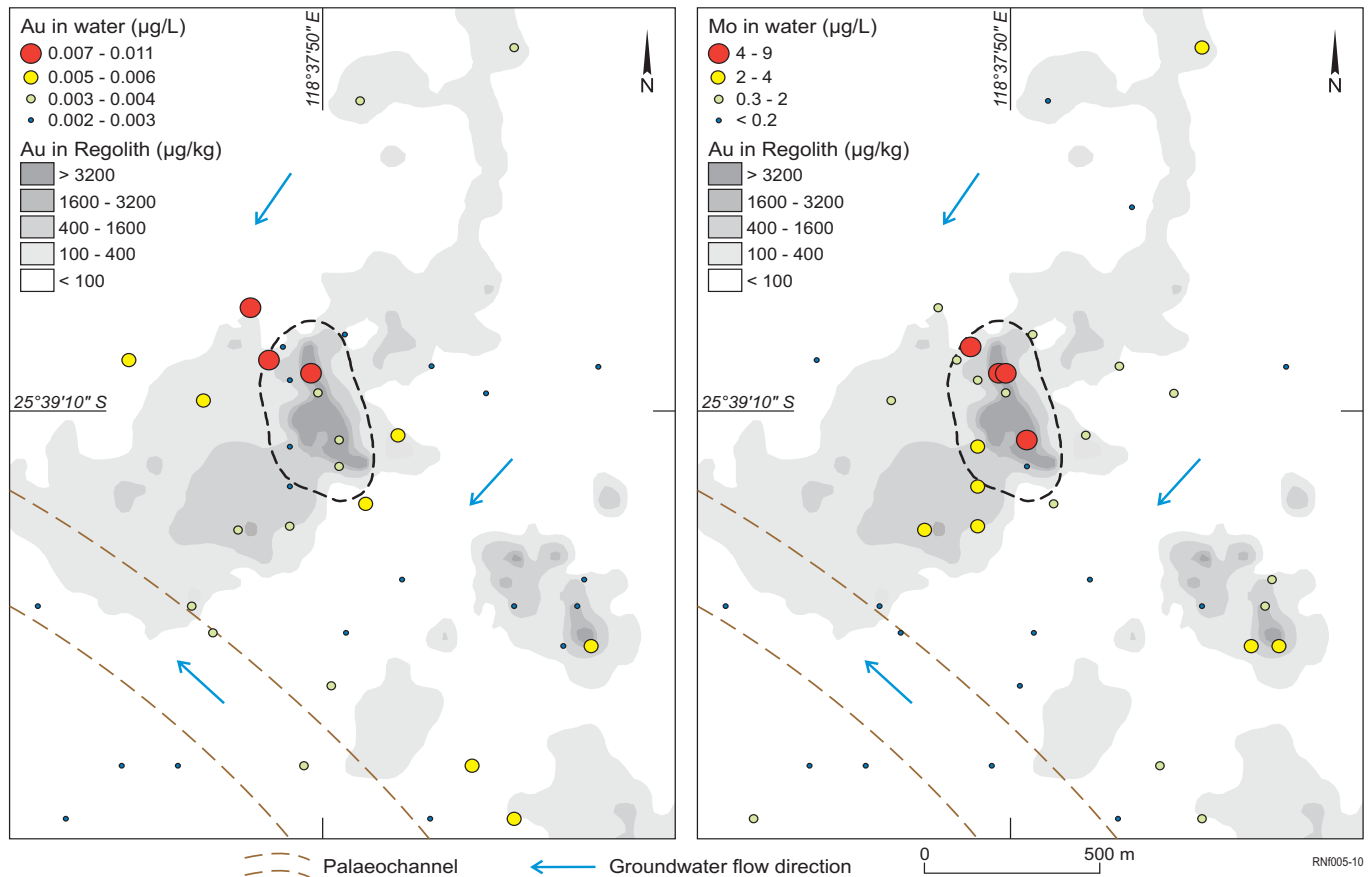


Figure 2. Dissolved Au (top) and Mo (bottom) concentrations in groundwater at the Baxter/Harmony gold deposit (dots) superimposed on maximum Au concentrations in the regolith at the interface between colluvium and residuum at a depth ranging between 1 and 12 m. The pit outline is shown towards the centre. The palaeochannel outline and the direction of ground water flow are also depicted.

duricrust of approximately 8 m thickness. A palaeochannel drains from 1 km south of the deposit in a northwest direction (Fig. 2). The palaeochannel is filled with 10-24 m of mottled, thick, puggy, clay-rich sediments (Robertson 2001).

The shallow aquifer groundwater <2 km from the Baxter deposit has a neutral pH, is fresh and generally similar to those from the northern Yilgarn Craton. The groundwater flows southeast, towards the channel. Approximately 40 samples were collected from drill holes over a 6 km² area. Dissolved Au concentrations are low (2-11 ng/L) and ~100 times less than in mineralized areas around Kalgoorlie. Despite these low concentrations, dissolved Au is a good pathfinder for mineralization in the Baxter region (Fig. 2).

Some groundwater has concentrations of Au below detection over mineralization that may indicate inconsistencies in Au mobility in this environment. Additionally, Sc, Mo (Fig. 2), W and possibly Rb have elevated groundwater concentrations in areas of Au mineralization and are more consistent pathfinders than Au itself in groundwater at this local scale. This elemental suite is similar, though more limited, to those observed elsewhere in the NE Yilgarn for detecting Au mineralization.

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Chromium in groundwater may be used to indicate underlying ultramafic lithologies in this region (Gray & Noble 2006). Chalcophile elements (e.g. As, Mo, Ag, Sb, W, Tl and Bi) are commonly enriched and more mobile in neutral groundwater in direct contact with weathering sulfides, suggesting *regional* groundwater sampling may be effective at locating these types of deposits.

Groundwater PGE for nickel exploration – a greenstone belt investigation

The Norseman-Wiluna greenstone belt extends through the NE Yilgarn Craton (Fig. 1) and hosts numerous major Ni deposits. The area is semi-arid to arid and has a Mediterranean climate with hot, dry summers and cool, wet winters. Mean annual rainfall is between 200-300 mm, similar to the Harmony study site (Bureau of Meteorology 2008). Mulga dominates the vegetation with minor drought-resistant shrubs and grasses. The primary land use is cattle grazing and mining.

Greenstones, including ultramafic and mafic volcanics, are enclosed within granitoids. This greenstone belt is abundantly mineralized, hosting numerous Ni sulfide deposits, including Cosmos, Honeymoon Well (Wedgetail, Corella, Harrier, Hanibals), Harmony, Mt Keith, Perseverance, Prospero, Rocky's Reward, Sinclair, Waterloo, Weebo and Yakabindie (Six Mile Well/Goliath). Most mineralization is in stratiform volcanic-hosted deposits, related to komatiite flows (Morris & Sanders 2001). The mineralization is varied massive, disseminated, matrix and remobilized stringer and breccia hosted sulfide mineralization of pentlandite and pyrrhotite. The sulfides

also contain significant concentrations of Platinum Group Elements (PGE). A comprehensive review of the geology and Ni mineralization styles and settings is given by Barnes (2006).

The topography is broadly flat with ancient alluvial transported cover of varied thickness (a few metres to tens of metres). Soils are dominantly acidic, sandy with red-brown hardpans and lack significant calcrete horizons except in channels. A comprehensive review of the regolith and geomorphology of the region is given by Anand & Paine (2002). The watertable along the greenstone belt is 10-40 m below surface.

The groundwater study included approximately 300 samples from in and around eight deposits along 160 km of the Norseman-Wiluna greenstone belt between Leonora and Wiluna. Gray & Noble (2006) investigated the evolution of groundwater and the hydrogeochemical signature related to sulfide weathering. The concentration of Pt and Pd in the groundwater was determined as part of this study using preconcentration onto activated carbon sachets (Noble & Gray 2010; Giblin 2001; Gray 2001). This method showed Pt and Pd (and W) are a useful vector to Ni mineralization (Fig. 3). The concentrations of PGE in the NE Yilgarn groundwater is very low (commonly <1 ng/L), making the use of these elements as pathfinders difficult. Samples of >1 ng/L (detection) are considered anomalous. Results show that higher concentrations of Pt, as well as any detectable Pd, are found mostly within 2 km of mineralization (Fig. 3). At Honeymoon Well, the four mineralized zones are all delineated with detectable Pt (>1 ng/L, Fig. 3).

The deposits all have elevated, but sporadic, Pt concentrations in the groundwater around the deposits. The lack of a PGE groundwater signature does not indicate an absence of Ni sulfide mineralization (i.e. could be a false negative), but a positive PGE result is a strong indicator of mineralization. The groundwater around the Jaguar VMS Zn deposit (Fig. 3) is also enriched in PGE, indicating that PGE in groundwater may be indicators of several different types of sulfide mineralization. The Ni sulfide mineralization in the Norseman-Wiluna greenstone belt contains significant PGE concentrations, but the weathering rates and mobility of PGE means concentrations are expected to be limited. Regardless, the use of PGE is more effective than the direct measurement of the target element (Ni for NiS deposits and Zn and Cu for the VMS deposits) alone. Nickel, Zn and Cu in groundwater are commonly adsorbed by clays and Fe-oxides and, as a result, the soluble concentrations are erratic, and often below detection, and do not commonly produce coherent anomalies around the sulfide mineralization.

Improving the detection limit for PGE in groundwater may significantly enhance exploration success using hydrogeochemistry for Ni sulfides and VMS in Australia.

Groundwater U from farm wells and bores – a regional scale investigation

Previous work has demonstrated that groundwater geochemistry can provide large geochemical signatures (Gray & Noble 2006; Cameron & Leybourne 2005). Uranium is

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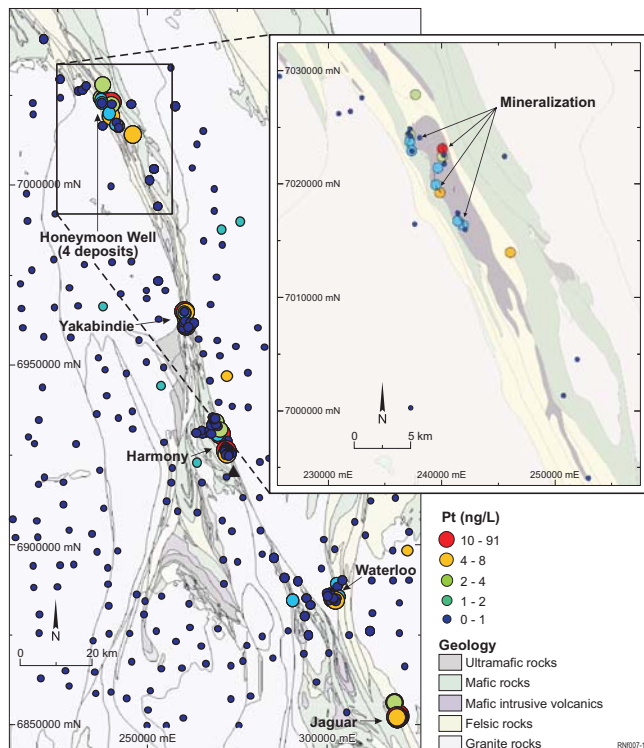


Figure 3. Platinum concentration in groundwater of the Norseman Wiluna greenstone belt in the NE Yilgarn, with a more detailed depiction of the Honeymoon Well area (mineralization is red). Grid coordinates are UTM Zone 51, GDA 94.

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generally mobile in groundwater and surface water and, in previous work, has shown geochemical haloes around U mineralization (Cameron 1980; Mann & Deutscher 1978; Peuraniemi & Aario 1991). A research project by the CSIRO Minerals Down Under Flagship assessed the value of low-density groundwater sampling (>5 km sample spacing) for mineral exploration and environmental management (Gray *et al.* 2009). The groundwater project objectives and spacing are similar to the successful laterite geochemistry project of the Yilgarn Craton (Cornelius *et al.* 2008) that showed large geochemical signatures in laterite, but spatially the two projects have only a minor overlap. This paper will only discuss some of the U results from the regional groundwater study.

The northeast Yilgarn Craton consists of Archaean granites and granitic gneiss and extensive northeast oriented, elongate greenstone belts (Williams 1975; Myers 1997). Cassidy *et al.* (2006) summarises the tectonic evolution of the Yilgarn Craton. The granitic rocks comprise deformed and metamorphosed granodiorite-monzogranite. The greenstones generally comprise mafic and ultramafic volcanic rocks underlain by quartzite, banded iron formation and minor felsic volcanics.

The climate and landforms are similar to those mentioned in the previous case studies. The northeast Yilgarn regional study covered approximately 470 x 250 km or 92 000 km² (Fig. 1) with numerous Ni (sulfide and

laterite), Au (orogenic) and U (secondary carnotite) ore systems, as well as several Zn (VMS) deposits (including the area of the previous greenstone belt case study).

Secondary carnotite style deposits (calcrete uranium) are prevalent along the drainage systems throughout the region, and include the world class Yeelirrie deposit, Lake Maitland, Centipede, Lake Way and the Cogla Downs/Hillveiv prospects (Fig. 4).

Groundwater samples (1420) were collected from farm wells and bores on ~5 km spacing where available. Regionally, the groundwater is relatively fresh and of neutral pH. Salinity tends to increase towards the drainages and valley floors where, in many cases, there are salt lakes. This is also the region where soluble U precipitates as carnotite.

Dissolved U alone is a reasonable targeting element on the ~5 km sample spacing, confirming the findings of Cameron (1980) and Mann & Deutscher (1978). Uranium concentrations in the northeast Yilgarn range from 1 to 700 µg/L (Fig. 4). In particular, the greatest U concentrations are close to the Yeelirrie deposit (along the drainage flow), identifying the Yeelirrie area as the strongest target (Fig. 4). Other known deposits also have elevated U concentrations compared to the background, with most of the known deposits occurring close to the larger (>100 µg/L) U groundwater concentrations. These larger U concentrations are consistently in the topographically lower parts of the landscape (drainage channels). Exceptions to this are the

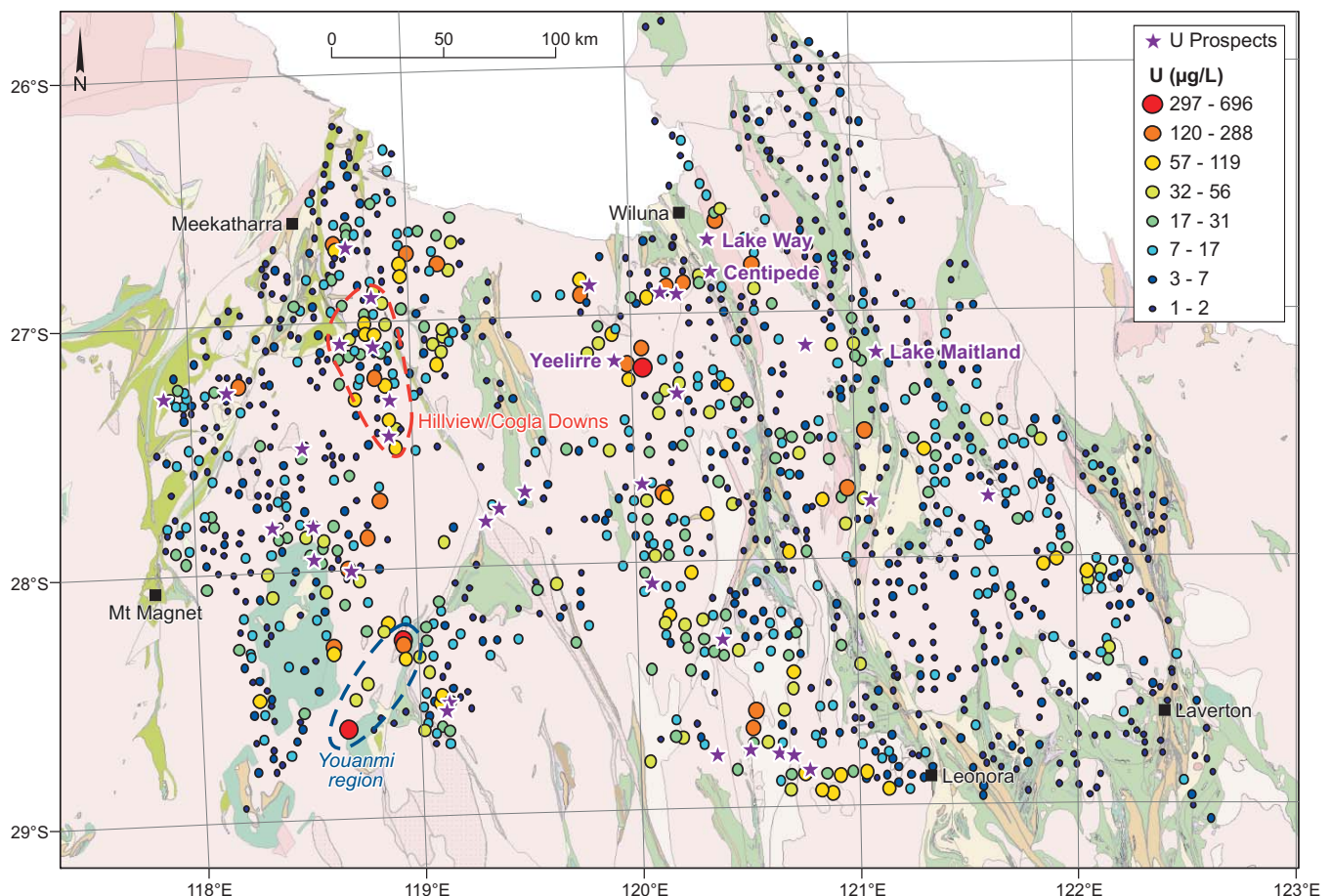


Figure 4. Northeast Yilgarn groundwater U concentrations. Major U deposits are labelled. Coloured polygons indicate major greenstone (green), granite (pink), felsic (yellow) and sedimentary (brown) lithologies. Black lines are faults.

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second and third largest concentrations of U > 297 µg/L towards the southwest of the study area in the Youanmi region (Fig. 4), which occur adjacent to the drainage divide and are in regionally elevated terrain. This particular area of elevated U concentrations in groundwater is unrelated to the palaeochannel/playa style deposits, and more likely reflects a primary ore source (this area does not show a surface radiometric response).

Uranium concentration alone does not strongly identify the second largest known deposit, at Lake Maitland, but this deposit is unusual because it occurs over greenstone bedrock (Fig. 4). Mineral saturation indices directly compute the activity of various chemical species, incorporating master variables such as pH and Eh of the system and, in turn, determine if the water is over- or under-saturated with respect to specific minerals. The carnotite saturation index (SI) is a direct measure of the potential for such deposits to form in palaeochannel or playa deposits. Spatially, the carnotite SI is more predictive than the U concentration and predicts most of the known deposits and prospects. The SI results for carnotite, reported in Gray *et al.* (2009), show the gradation of groundwater approaching saturation along the channels that corresponds to the location of the deposits. The carnotite SI also indicates that the groundwater upstream from Lake Maitland is close to saturation.

CONCLUSIONS

Groundwater sampling provides significant exploration potential at different scales in Western Australia, even where highly weathered rocks are overlain by transported material. Target and pathfinder element signatures may be much broader than geochemical haloes in other media and extension of hydrogeochemical exploration to sediment obscured Craton margins could be a cost-effective and viable technique for exploration in these areas. Comparison studies between sample media are required and the relationships between the laterite geochemistry data (Cornelius *et al.* 2008) and the groundwater data (where the two sets overlap) is presently being conducted. Improving detection limits for PGE in groundwater will most likely enhance the exploration success for Ni sulfides using hydrogeochemistry in arid and semi-arid regions of Western Australia.

An added benefit of mineral exploration using groundwater is that it provides additional data for

monitoring human and livestock drinking water supplies, baselines for future hydrogeochemical exploration and environmental management (e.g. mine closure).

In addition to the groundwater regional study (Gray *et al.* 2009), a biogeochemical mapping project using 1400 mulga (*A. aneura*) samples has been started and will be completed by late 2010. This project will investigate the links between the regional groundwater chemistry and vegetation chemistry in the northeast Yilgarn, and provide the first large scale biogeochemical map in Australia. For additional information please contact the authors.

ACKNOWLEDGEMENTS

The support of CRC LEME and CSIRO Minerals Down Under Flagship program and assistance from Dale Longman and Mark Pirlo is appreciated. Travis Naughton and Angelo Vartesi are thanked for production of the figures. Research summarized was sponsored from a number of sources, in particular CSIRO/AMIRA P240, P241, P241A, P409, P504, MERIWA, and a project on Ni hydrogeochemistry supported by CRCLEME, BHP Billiton, Inco, Lion Ore and Anglo American. The sponsors of all these projects are thanked for their generous support. Matthew Leybourne, Beth McClenaghan, Mel Lintern and Ravi Anand are thanked for reviewing this manuscript.

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